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Detailed Fission Power 2D-Mapping of AFIP-2 Experiment in ATR CFT Position

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ABSTRACT

The NNSA (National Nuclear Security Administration) RERTR (Reduced Enrichment for Research and Test Reactors) program assigned INL (Idaho National Laboratory) the responsibility of developing and demonstrating high uranium density research reactor fuel forms to enable the use of low enriched uranium (LEU) in the research reactors around the world. A series of full-size fuel plate irradiation tests are proposed for the ATR (Advanced Test Reactor). Labeled the AFIP *(**A**TR* **F**ull-size-plates ***In*** center flux trap **P**osition) experiments, these tests will be conducted in the ATR center flux trap.

The nominal fuel zone is rectangular in shape having a designed length of 21.5-in (54.6l-cm), width of 1.6-in (4.064-cm), and uniform thickness of 0.014-in (0.03556-cm). This gives a nominal fuel zone volume of 0.482 in^3 (7.89 cm^3) in each fuel plate. The test holder accommodates two independent test trains. Each test train is designed to hold 2 plates, for a total of 4 plates per test holder.

AFIP-2 test plates will be irradiated at a peak surface heat flux of about 350 W/cm^2 and discharged at a peak U-235 burn-up of about 70 at.%. Based on limited irradiation testing of the monolithic (U10Mo) fuel form, it is desirable to keep the peak fuel temperature below 250°C; to achieve this, it will be necessary to keep plate heat fluxes below 500 W/cm^2. Due to the heavy U-235 loading and width of 1.6-in (4.064-cm), the neutron self-shielding will increase the local-to-average-ratio fission power near the sides of the fuel plates. To assure the AFIP-2 experiment will comply with the ATR safety requirements, a very detailed 2-dimensional (2D) Y-Z fission power profile was evaluated to best predict the fuel plate temperature distribution.

The ability to accurately predict fuel plate power and burnup are essential in the AFIP-2 fuel test train design and the irradiated fuel performance evaluation. We obtained the required power and heat generation rates within test train for the thermal analyses. A detailed MCNP Y-Z mini-plate fuel model was developed. The Y-Z model divides each fuel mini-plate into 30 equal intervals in Y and Z directions. The MCNP-calculated results and the detailed Y-Z fission power mapping were used to help design the AFIP-2 fuel test assembly to ensure that the capsule thermal-hydraulic limits will not exceed the ATR safety limit.

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INTRODUCTION

The NNSA (National Nuclear Security Administration) RERTR (Reduced Enrichment for Research and Test Reactors) program assigned INL (Idaho National Laboratory) the responsibility of developing and demonstrating high uranium density research reactor fuel forms to enable the use of low enriched uranium (LEU) in the research reactors around the world. A series of mini-size high density fuel plates irradiation tests (RERTR-5, -6, -7, -8, and -9) have been successfully completed and are undergoing Post-Irradiation Examination (PIE) at INL. A new series of full-size fuel plate irradiation tests are proposed for the Advanced Test Reactor (ATR). Labeled the AFIP *(**A**TR* **F**ull-size-plates ***In*** center flux trap **P**osition) experiments, these tests will be conducted in the ATR center flux trap.

The full size LEU fuel test (AFIP-2) focuses on irradiation testing of monolithic (U10Mo) fuel with U-235 enrichment of 19.7 wt%. As fuel performance is demonstrated, power and burn-up targets will increase to about 70 at.% LEU equivalent U-235 burn-up. The AFIP experiment series will include the capability for measuring plate swelling as a function of burn up through the in-canal measurement of plate thickness between cycles. Plate assemblies that show signs of unusual behavior can be pulled from the test train.

AFIP-2 test plates will be irradiated at a peak surface heat flux of about 350 W/cm^2 and discharged at a peak U-235 burn-up of about 70 at.%. Based on limited irradiation testing of the monolithic (U10Mo) fuel forms, it is desirable to keep the peak fuel temperature below 250°C; to achieve this, it will be necessary to keep plate heat fluxes below 500 W/cm^2. Due to the heavy U-235 loading and the width of 1.6-in (4.064-cm), the neutron self-shielding will increase the local-to-average-ratio fission power near the sides of the fuel plates. To assure the AFIP-2 experiment will comply with the ATR safety requirements, a very detailed 2-dimensional (2D) Y-Z fission power profile was evaluated to best predict the fuel plate temperature distribution.

The ability to accurately predict fuel plate power and burnup are essential in the AFIP-2 fuel test train design and the irradiated fuel performance evaluation. We obtained the required power and heat generation rates within test train for the thermal analyses. A detailed MCNP Y-Z mini-plate fuel model was developed. The Y-Z model divides each fuel mini-plate into 30 equal intervals in Y and Z directions. The MCNP-calculated results and the detailed Y-Z fission power mapping were used to help design the AFIP-2 fuel test assembly to ensure that the capsule thermal-hydraulic limits will not exceed the ATR safety limit.

2D-MAPPING METHODOLOGY

MCNP[1] has a built-in mesh tally, which can use the plotting software render the 3-D tally into a contour plot. Let us assume there is a tally volume of 30×30×30 cm^3, which is sub-divided to 60×60×60 tiny volume cells. Let us also assume that the CPU for the one big whole volume cell MCNP-calculation to achieve a standard uncertainty band (1σ) is 200 seconds. Then, to achieve the same 1σ as for a one big whole volume cell, CPU of the 3-D mesh tally of the subdivided cells would be 30×30×30×200 seconds, which would be a very long and un-acceptable waiting time. In this work, for the homogenized full size plate, we can assume the small sub-cell tallies T_{xyz} can be represented by $T_x \times T_y \times T_z$. The CPU of the T_x x T_y x T_z to achieve the same 1σ as for a one big volume cell would be 3×30×200 seconds, which represents a saving of 300 CPU times. For 2D-mapping method used in this paper, $T_{yz} = T_y \times T_z$ would have a CPU saving of 15 times.

AFIP FUEL TEST ASSEMBLY MODEL

The AFIP test assembly is positioned in the center flux trap (CFT) of the ATR as shown by Figure 1. All structural components of the AFIP test assembly are Al-6061. The AFIP-2 irradiation test assembly contains one fuel column comprised of two monolithic type fuel plates and one blank fuel column comprised of an aluminum dummy. The fuel column is located in position A and the aluminum dummy column is located in position B as shown in **Error! Reference source not found.**.

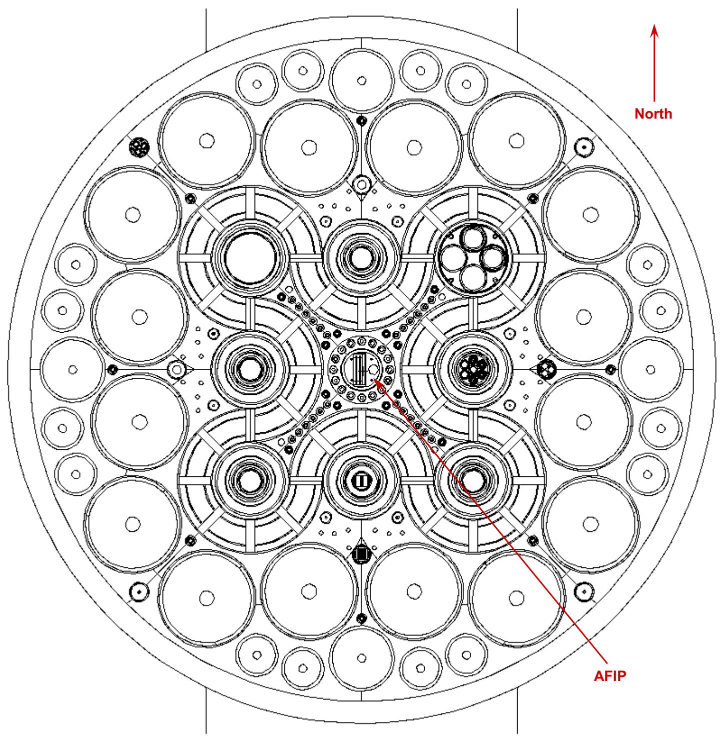

Figure 1. MCNP-generated cross sectional view of the three-region ATR core with the AFIP test assembly in the CFT.

Table 1. AFIP-2 Fuel Plate Nominal Constituent Masses

Fuel Plate Position	Fuel Type	Fuel Phase Composition	U-235 Enrichment (%)	Fuel Phase Mass U-238 (g)	U-235 (g)	Mo (g)
A-1	foil	U-10Mo	20%	97.1	23.82	12.27
A-2	foil	U-10Mo	20%	97.6	23.82	12.27

The nominal fuel zone is rectangular in shape having a designed length of 21.5-in (54.6l-cm), width of 1.6-in (4.064-cm), and uniform thickness of 0.014-in (0.03556-cm). This gives a nominal fuel zone volume of 0.482 in^3 (7.89 cm^3) in each fuel plate. The test holder accommodates two independent test trains. Each test train is designed to hold 2 plates, for a total of 4 plates per holder.

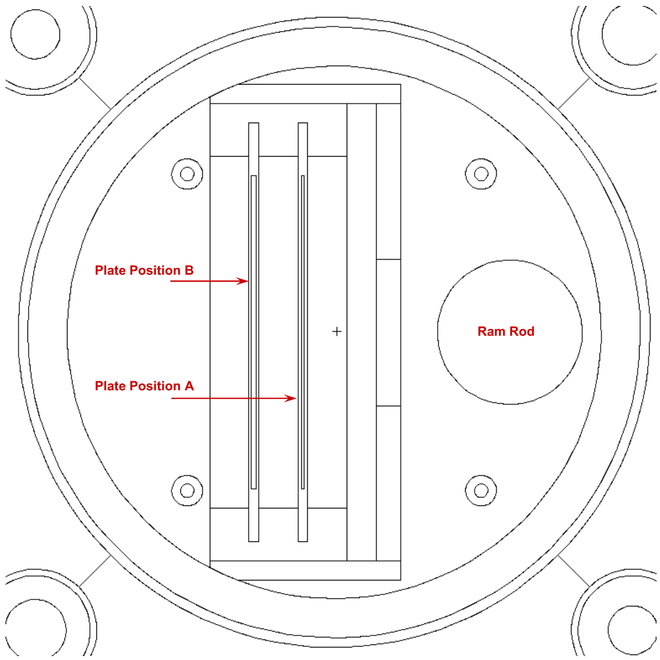

Figure 2. MCNP-generated cross sectional view of the AFIP-2 test assembly.

RESULTS and DISCUSSION

To build the 2D-mapping T_z model, we divided the plate upper A-1 and lower A-2 length into 30 equal intervals for a total of 60 sub-divide cells. For 2D-mapping T_y model, we divided the plate upper A-1 and lower A-2 width also into 30 equal intervals with a total of 60 cells. For each model MCNP run, we used $6x10^8$ neutron source particles to achieve 1σ of 0.0044. The CPU time for each case run on HELIOS (126 nodes w/dual core Intel Xeon 5150 processors (2.66 GHz), 8 GB RAM, 40 nodes w/quad core Intel Xeon X5355 processors (2.66 GHz), 16 GB RAM) High Computing Center with 50 nodes in parallel was 105 minutes. The MCNP-calculated local to average ratio (L2AR) of T_z-60 and T_y-60 are tabulated in Table 2.

For plate A-1, AZ-30 and for plate A-2, AZ-1 are both nearest the core axial mid-plane with a Al Spacer gap of 4.71" (11.96 cm). The Tz peak L2AR for plate A-1 at AZ-30 and plate A-2 at AZ-1 are 1.368 and 1.279, respectively. The neutron self-shielding effects are apparent across the plates, the Ty peak L2RA of 1.045 are at the two side-end of the full-size fuel plate. The 2D-plot of the vector product of Tz and Ty for each plate are shown in Figure 3. The Figure 3 clearly shows that there are two peaks of L2AR at the AZ-1 and AZ-30 full fuel plate corner edges.

Table 2. MCNP-calculated T_z-60 and T_y-60 L2RA fission power profiles.

Interval	Plate A-1 Tz L2AR	Plate A-2 Tz L2AR	Interval	Plate A-1 Ty L2AR	Plate A-2 Ty L2AR
AZ-1	0.424	1.279	AY-1	1.047	1.045
AZ-2	0.478	1.229	AY-2	1.017	1.017
AZ-3	0.529	1.216	AY-3	1.006	1.020
AZ-4	0.578	1.209	AY-4	1.009	1.009
AZ-5	0.632	1.207	AY-5	1.002	1.011
AZ-6	0.682	1.202	AY-6	0.998	1.004
AZ-7	0.735	1.197	AY-7	1.008	1.007
AZ-8	0.784	1.184	AY-8	1.000	1.001
AZ-9	0.829	1.177	AY-9	0.994	0.990
AZ-10	0.871	1.175	AY-10	0.984	0.990
AZ-11	0.919	1.161	AY-11	0.992	0.992
AZ-12	0.963	1.140	AY-12	0.993	0.988
AZ-13	1.001	1.131	AY-13	0.984	0.982
AZ-14	1.034	1.106	AY-14	0.981	0.989
AZ-15	1.068	1.086	AY-15	0.987	0.984
AZ-16	1.100	1.073	AY-16	0.982	0.982
AZ-17	1.127	1.043	AY-17	0.981	0.983
AZ-18	1.148	1.016	AY-18	0.982	0.985
AZ-19	1.174	0.981	AY-19	0.988	0.990
AZ-20	1.201	0.948	AY-20	0.989	0.989
AZ-21	1.213	0.920	AY-21	0.988	0.988
AZ-22	1.231	0.880	AY-22	0.988	0.986
AZ-23	1.242	0.837	AY-23	0.993	0.995
AZ-24	1.253	0.794	AY-24	1.008	0.993
AZ-25	1.263	0.747	AY-25	1.000	0.998
AZ-26	1.280	0.703	AY-26	1.008	1.002
AZ-27	1.283	0.665	AY-27	1.008	1.002
AZ-28	1.288	0.613	AY-28	1.020	1.011
AZ-29	1.300	0.570	AY-29	1.023	1.021
AZ-30	1.368	0.514	AY-30	1.039	1.045

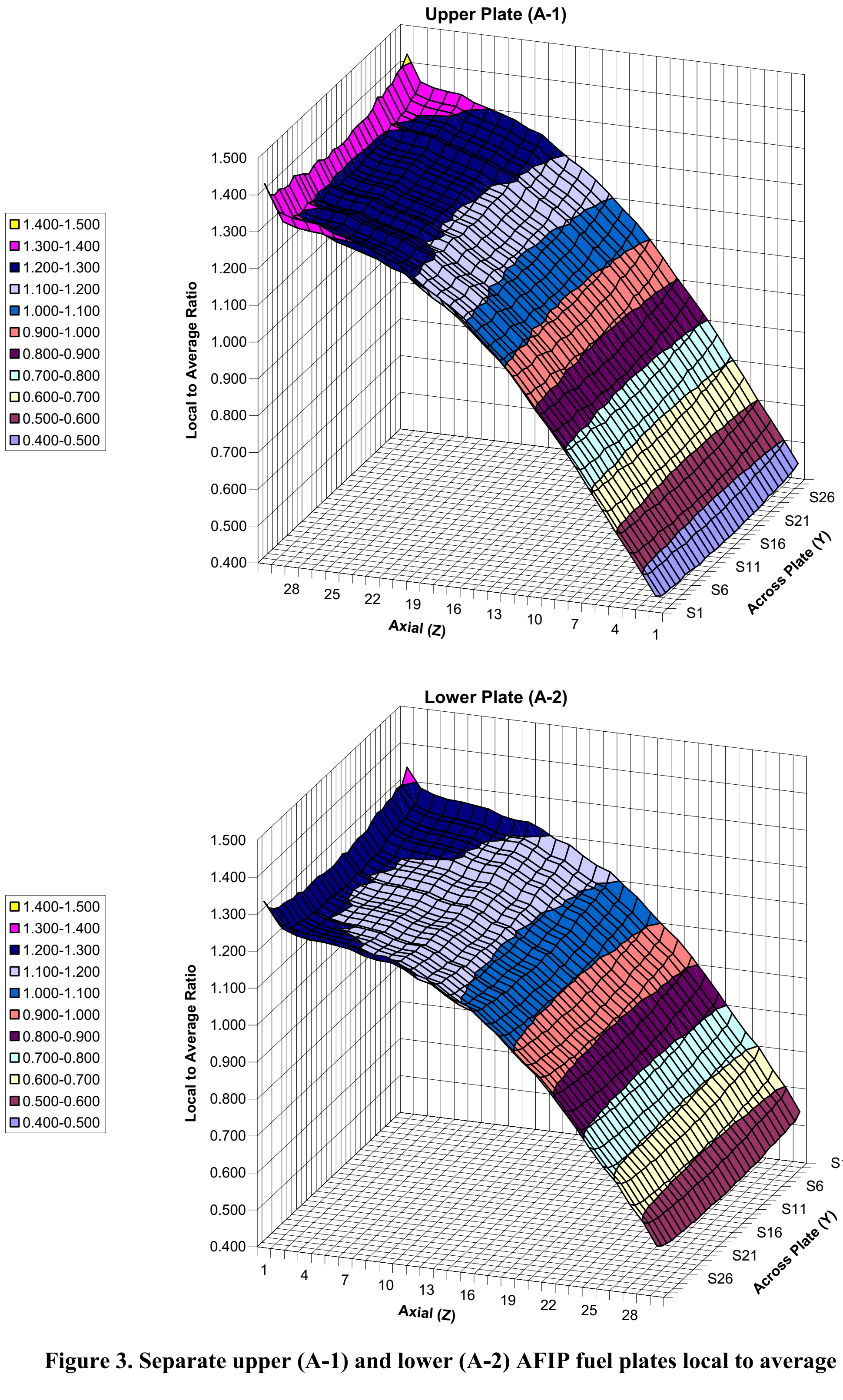

Figure 3. Separate upper (A-1) and lower (A-2) AFIP fuel plates local to average ratio plots.

CONCLUSION

The 2D-mapping method used in this paper, $T_{yz} = T_y \times T_z$, can achieve the same 1σ with a saving CPU run-time of 15 times. The MCNP-calculated highly accurate L2AR of T_z-30 and T_y-30 profiles were providing for the test assembly design thermal-hydraulic analysis to ensure that the capsule thermal-hydraulic limits will not exceed the ATR safety limit. The 2D-mapping method has been successfully used to provide RERTR an accurate fission power gradient profile for the fuel performance evaluation.

REFERENCES

1. X-5 Monte Carlo Team, "MCNP—A General Monte Carlo N-Particle Transport Code, Version 5," Volume I (LA-UR-03-1987) and Volume II (LA-CP-0245), Los Alamos National Laboratory April 24, 2003 (Revised 6/30/2004).